

# ACTS Broadband Aeronautical Terminal

M.J. Agan, A.C. Densmore

Jet Propulsion Laboratory, California Institute of Technology  
4800 Oak Grove Drive  
Mail Stop 238-420  
Pasadena, California 91109

Phone: (81 8) 354-3426 FAX: (818) 354-6825 E-mail: [agan@bvd.jpl.nasa.gov](mailto:agan@bvd.jpl.nasa.gov)

## ABSTRACT

This paper will discuss the design of, and experiments with, the ACTS Broadband Aeronautical Terminal. As part of the ongoing effort to investigate commercial applications of ACTS technologies, NASA's Jet Propulsion Laboratory and various industry/government partners are developing a broadband mobile terminal for aeronautical applications. The ACTS Broadband Aeronautical Terminal is being designed and developed to explore the use of **K/Ka-band** for high data rate aeronautical satellite communications. Currently available commercial aeronautical satellite communications systems are only capable of achieving data rates on the order of tens of kilobits per second. The broadband terminal, used in conjunction with the ACTS mechanically **steerable** antenna, can achieve data rates of 384 **kilobits per second**, while use of an ACTS spot beam antenna with this terminal will allow up to T1 data rates (1.544 megabits per second). The aeronautical terminal will be utilized to test a variety of applications that require a high data **rate** communications link. The use of the **K/Ka-band** for wideband aeronautical communications has the advantages of spectrum availability and smaller antennas, while eliminating the one major drawback of this frequency band, rain attenuation, by flying above the clouds the majority of the time.

## INTRODUCTION

Since shortly **after** the launch of the ACTS in September, 1993 the NASA/JPL developed ACTS Mobile Terminal (AMT) [ref x] has been conducting land-mobile satellite experiments in conjunction with a variety of **industry** partners. Much has been learned about this communications channel as a result of these experiments [ref **brian arnsc** paper]. A natural extension of these experiments was to investigate the **K/Ka-band** aeronautical communications channel by installing and testing the AMT in an aircraft. The results of these experiments are described in [ref **sohn imsc** paper]. Building on these aeronautical experiments the ACTS Broadband Aeronautical **Terminal** was designed to operate at higher data rates (2384 kbps vs. **4.8 kbps**), and without restrictions on the flight path or aircraft dynamics.

The specific experimental objectives with this terminal are to: (1) demonstrate and characterize the performance of high data rate aeronautical **Ka-band** communication (2)

characterize the propagation effects of the communications channel during take-off, cruise, and landing phases of flight, (3) provide the systems/technology groundwork for an eventual commercial Ka-band aeronautical satellite communication system.

## USE OF ACTS

ACTS is an experimental **K/Ka-band** satellite launched by NASA to explore advanced communication satellite technologies [acts reference]. Positioned in geosynchronous orbit at 100° W longitude, ACTS transmits at 20 GHz and **receives** at 30 GHz. This experiment requires ACTS to operate in the baseband processor mode, in which it behaves as a bent-pipe transponder. The ACTS LA/San Diego spot beam will be used to establish the communication link between the **fixed** term **inal** at JPL and ACTS. The ACTS 1 meter diameter mechanically steerable dish **antenna** will be used to establish the link between ACTS and the aircraft.

The use of the ACTS steerable dish distinguishes this experiment from the previous ACTS land mobile and aeronautical mobile experiments in that they utilized the ACTS spot beam to illuminate the mobile terminal. The benefit of using the steerable antenna is that it removes the restriction that **the** flight path be within spot beam contours, allowing the aircraft to fly anywhere in the Western hemisphere. The drawback of using the ACTS steerable antenna is that it is smaller and thus has lower gain than the spot beam antennas, approximately 6 **dB** less on transmit and receive. This decrease in satellite antenna gain was in part overcome by designing an higher gain antenna on the aircraft, .

Use of the ACTS steerable antenna introduces the additional complication of requiring the antenna to continuously track the **aircraft**. The ACTS steerable antenna has a 3 **dB** contour of 280 miles, which coupled with a maximum aircraft ground speed of 700 mph, results in a low dynamic tracking problem. This tracking is accomplished by multiplexing aircraft positioning information (GPS latitude and longitude) with the data stream transmitted from the **aircraft** to the fixed terminal located at JPL. At the fixed terminal the positioning information is then **demultiplexed** and transmitted via the public switched telephone network (**PSTN**) to the ACTS

control station, where the ACTS is then commanded to point the steerable antenna to this aircraft location.

## TERMINAL DESIGN

A block diagram of the aeronautical mobile terminal is presented in Figure 1. The terminal development leverages off the technologies developed under the AMT project at JPL. As such the RF converter, IF converter, and Data Acquisition System (DAS) subsystems have been adapted from their AMT land mobile designs to operate in the higher dynamic aeronautical environment. The antenna, power amplifier, modem, and video codec were designed/specified specifically for this aeronautical application. The JPL fixed terminal equipment is essentially equivalent to that in the aircraft with the exception of the 2.4 meter ground antenna.

The link budgets for the forward link (JPL fixed terminal-ACTS-aircraft), and the return link (aircraft-ACTS-JPL fixed terminal) are given in Table 1. Not shown in the link budgets for simplicity is the forward link pilot signal. The pilot is transmitted from the fixed terminal to the aircraft to as an aid in antenna tracking, Doppler compensation, and link characterization. More detailed descriptions of the subsystems follow.

### Video Codecs

The commercial video codec will compress/decompress full motion video in real time as well as multiplex the aircraft position information into the data stream which is then passed to the modem. The video codecs are existing (off-the-shelf) codecs. In an effort to select an appropriate video codec for the aeronautical mobile satellite communication environment, codec requirements were specified, an exhaustive survey of video codec manufacturers was performed, and trials of three codecs were conducted at JPL. A summary of the codec requirements is given in Table 2. The surveyed video codec manufacturers included: Compression Labs, VTEL, NEC, British Telecom, Panasonic, ABL, Hitachi, PictureTel, Mitsubishi, Horizons, UVC, and a variety of compression board manufacturers. A crucial part of this survey was attending the annual Video Telecommunications Conference (VTC) to make qualitative evaluations of the video quality at the data rates of primary interest. Circumstances were such that after the list of candidates was narrowed, actual laboratory tests and satellite experiments were performed with the ABL, CLI, and NEC video codecs.

The ideal video codec for aeronautical mobile applications has characteristics that are not necessarily important when the codecs are utilized in their traditional role of fixed site video teleconferencing. The aeronautical mobile satellite communications channel may have periods of signal outage due to aircraft structure shadowing or the keyhole effect. Signal outages necessarily require the video codec to regain synchronization rapidly when the signal returns. The best

outage recovery performance that could be had with existing video codecs was on the order of three seconds after the codec started receiving valid data. The mobile satellite communications channel typically has a higher bit error rate than do the communication channels which the video codecs typically encounter. As a result it is critical that the codec degrade gracefully in the presence of high bit error rates and, again recover rapidly from these errors. Some video codecs were found to have a tendency to "hang" or freeze in the presence of high bit error rates, requiring the power to be cycled,

Other required codec features that are not as important in fixed site applications are that the codec be small in size, light in weight, somewhat rugged in construction, and capable of multiplexing multiple external data sources with the compressed video data stream.

In evaluating the codec video quality the performance at data rates from 128 kbps to 384 kbps was deemed to be most important for the planned mobile SATCOM experimental applications. Most video codecs were found to provide very good quality video at data rates approaching T1 (1,544 Mbps), but there were significant differences in quality at the data rates of interest. Quality varied significantly, primarily in image resolution, but also in motion handling capability. All the video codecs had their own advantages and disadvantages, but on the whole the NEC video codec was determined to be the currently available codec most appropriate for the aeronautical experiments.

### Modem

The modem was designed to counteract the peculiarities of the K/Ka-band aeronautical communications channel, including varying frequency offsets, phase noise, and signal outages. BPSK modulation is combined with coherent demodulation, and error correction coding is provided by a concatenated code, a convolutional inner code (rate 1/2, constraint length 7) and a Reed-Solomon outer code (rate 239/256). A bit error rate of  $10^{-6}$  is achieved at an  $E_b/N_0$  of 3.0 dB.

Operation at higher bit rates, compared the AMT, allowed the use of coherent differential detection because the high close-in to the carrier phase noise can be tracked out by the wider bandwidth of the tracking loop. The receiver loop parameters also had to be optimized to allow Doppler frequency offsets of up to 30 kHz, varying at 900 Hz/sec to be tracked. Additionally the synchronization algorithms (carrier, bit, and decoder) had to be optimized to allow recovery synchronization within one second of signal presence. Commquest Technologies, Inc. modified a commercial satellite modem to meet these aeronautical requirements.

### RF Electronics

The IF **up/down** converter translates between 3.373 and a lower 70 MHz IF at the **output/input** of the modem. A key **function** of the IF converter is pilot tracking and Doppler **pre-compensation**. The **down-converted** pilot is tracked in a phase-locked loop and used as a frequency reference in the mobile terminal. The loop is capable of tracking out 39 kHz of Doppler varying at 900 Hz/sec. The **tracked** pilot is also processed in analog hardware and mixed with the up-converted data signal from the modem to **pre-shift** it to offset the Doppler on the return link. The IF converter provides the DAS and antenna subsystem with pilot signal strength for link characterization and antenna pointing operation **respect ively**.

Preceding (or following) the antenna the RF up (down) converter will convert an IF around 3.373 GHz to (from) 30 (20) GHz for transmit (receive) purposes. The RF interfaces directly to the antenna on the receive side of the link. On the transmit side the RF converter 30 GHz signal is goes to the traveling wave tube amplifier (TWTA). The TWTA supplies 100 Watts of transmit power to the passive reflector antenna.

#### *nna*

The high gain aeronautical antenna **will** employ an azimuth and elevation pointing system to allow it to track the satellite while the aircraft is maneuvering. The aeronautical antenna and **radome** are being developed by EMS Technologies, Inc. The EMS antenna design utilizes a slotted waveguide array, is mechanically steered in both azimuth and elevation, and is designed to enable mounting on a variety of aircraft. The radome is hat shaped with a peak height of 6.7" and a 27.6" diameter; roughly the size of the SkyRadio radome currently flying on United Airlines and Delta Airlines aircraft. Figures 2 and 3 show the antenna and installed radome respectively. Antenna installation requires a 3" **diameter** protrusion into the **fuselage** to allow the necessary signals to pass to and from the antenna.

The **antenna** is capable of tracking a full 360° in azimuth and -5° to zenith in elevation. The antenna RF requirements include that it maintain, in flight, a minimum transmit gain of 29 dBi and a minimum receive sensitivity of 0 dBm/K. Circular polarization is utilized and there exists the capability to transmit up to 120 Watts through the **antenna**. The actual dimensions of the combined transmit and receive array apertures, shown clearly in Figure 2, are less than 16 inches wide, and less than 4.5 inches in height.

The transmit array 3 dB **beamwidths** are 5° and 2.5° in elevation and cross-elevation respectively. The receive array 3 dB **beamwidths** are 7° and 4° in elevation and cross-elevation respectively. The antenna tracking mechanism is required to maintain pointing within 0.5 dB of **beampeak** throughout all phases of flight. This is accomplished through a tracking algorithm that utilizes three sources of information, an inertial rate sensor, the

aircraft Inertial Navigation System (INS), and pilot signal strength feedback from a circular dithering of the beam. The rate sensor provides the primary information for accurately pointing the antenna, with the INS and the dithering mechanisms being used to adjust for long term drift of the rate sensor.

#### *DAS*

The DAS performs continuous measurement and recording of a wide array of propagation, communication link, and terminal parameters to aid in the characterization of the communication channel (e.g., pilot and data signal conditions, noise levels, **antenna** direction, aircraft velocity, pitch, roll, yaw, etc.). The DAS also provides real-time displays of these parameters to aid the experimenters in the aircraft and in the fixed terminal,

#### *Current Terminal Status*

The aeronautical terminal is **currently** undergoing integration and testing in preparation for experiments that will commence in June 1995. The terminal is being integrated into the JPL **land** mobile van to allow convenient testing of subsystem **interconnectivity** and overall system performance prior to aircraft integration.

#### EXPERIMENTS

The initial two experiments to be conducted with the aeronautical terminal are shown in the accompanying Figures 4 and 5. The NASA Ames Research Center **will** be flying the terminal in the **Kuiper** Airborne Observatory (KAO) to transmit **imagery** from the **aircraft** for an educational broadcast and to conduct remote **tele-science**. Rockwell/Collins is working with JPL to develop the terminal and integrate it into a Rockwell **Saberliner** aircraft to demonstrate the transmission of compressed video both to and **from** the aircraft. Beyond these two experiments, several additional experiments with industry and government partners are in various stages of planning.

#### *KAO/ACTS Experiment*

JPL, working cooperatively with NASA Ames, will **be** conducting a series of experiments on the KAO that will **utilize** the ACTS. **These** experiments will take place from June through September 1995. The JPL developed ACTS Broadband Aeronautical Terminal will be installed in the KAO C-141 **aircraft** to allow the establishment of a **full-duplex** 384 kbps satellite communications link between the aircraft and the ground, and extend Internet into the **aircraft**. There are currently four planned components of this experiment, These are:

- 1) Television **broadcast/interactive** classroom - a PBS produced live television' broadcast entitled "Live **from** the Stratosphere". As part of the broadcast, students watching the live video transmitted **from** the aircraft

will be able to ask questions via voice link to the aircraft.

- 2) Video downlink to the San Francisco Exploratorium and Adler Planetarium in Chicago.
- 3) **Telescience** demonstration of remote control of scientific instruments onboard the KAO via an extension of Internet connectivity to onboard the aircraft.
- 4) System Health Monitoring demonstration of a system that remotely monitors scientific instruments onboard the KAO via Internet.

#### *Rockwell/Collins Experiment*

Rockwell International/Collins Corporation Commercial/Government Aeronautical Services Experiment

Rockwell and JPL are currently working together on an experiment design that will investigate the feasibility and limitations of airborne Ka-band satellite communications. This experiment involves the installation of the Broadband Aeronautical Terminal into Rockwell's **Saberliner 50** aircraft for a series of demonstration flights. The specific objectives of this experiment are to:

- 1) Determine the feasibility of high data rate communications, in particular compressed **full** motion video, to and from an airborne platform under varying weather conditions.
- 2) Determine the feasibility of slaving the steerable satellite antenna to an onboard **aircraft** Global Positioning System (GPS) **receiver** in order to automatically follow the flight path of the **aircraft**, allowing the highest possible data **rate** channel for critical applications.

This experiment has applications to both commercial aviation and government airborne services. Commercial airlines wish to offer live video and high bandwidth multimedia services to passengers, but currently do not have the necessary bandwidth capacity to/from the aircraft. Various government entities have mission requirements to transmit and receive real-time video between airborne mobile terminals and fixed earth terminals. This experiment is slated to take place during the latter part of 1995.

#### *Additional Experiments*

Presently there are two experiments are planned to follow the above two experiments. The first of these is a **Wildfire Research** and Disaster Assessment experiment that is described in more elsewhere in these proceedings [**shameson** reference]. Another currently planned experiment is planned with Vigyan, Inc. to transmit **real-time** graphical map information to the cockpit of an **aircraft**

in flight. Additional experiments being discussed involve **aeronautical** remote sensing applications for fixed wing and rotary wing aircraft, and a variety of military **aircraft** applications.

#### SUMMARY

JPL working with its industry partners has undertaken the development of a **pre-commercial** broadband aeronautical terminal to explore new applications and uses of **K/Ka-band** satellite communications. Actual flights and experimental results will be generated starting in June 1995 and made available to any parties interested in advancing the commercialization of the technology. Planned commercial satellite systems with which the equipment described in this paper could be utilized include the **K/Ka-band** systems proposed by Hughes (**Spaceway**), **Teledisic**, and Norris Communications.

#### REFERENCES

- [1] K. Dessouky and T. Jedrey, "The ACTS **Mobile Terminal**", Proceedings 14th AIAA Conference, March 22-26, 1992, Washington, DC.
- [1] M. Agan and A. Densmore, "Broadband **Aeronautical System**," IEEE M?T/National **Telesystems** Conference Proceedings, San Diego, CA, May 1994.
- [2] A. Densmore, M. Agan, H. Prather, M. Guler, M. Moody "An Aeronautical Mobile Terminal for High Data Rate 20/30 Ghz Satcom," to be published.
- [3] L. Shameson, J. Brass, J. Hanratty, A. Roberts, and S. **Wagener**, "Satellite Communications Provisions on NASA Ames Instrumented Aircraft Platforms for **Earth Science** Research/Applications", International Mobile Satellite Conference, **IMSC'95**, June 6-8, Ottawa,
- [4] P. Sohn, C. Raquet, R. Reinhart, D. Nakamura, "ACTS Aeronautical Terminal Experiment System Description and Link Analysis", International Mobile Satellite Conference, **IMSC'95**, June 6-8, Ottawa.
- [5] B. Abbe, and D. Pinck, "ACTS Aeronautical Terminal Experiment System Description and Link Analysis", International Mobile Satellite Conference, **IMSC'95**, June 6-8, Ottawa.
- [6] ACTS reference (NTC-gargione)? or other recent acts reference

#### ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

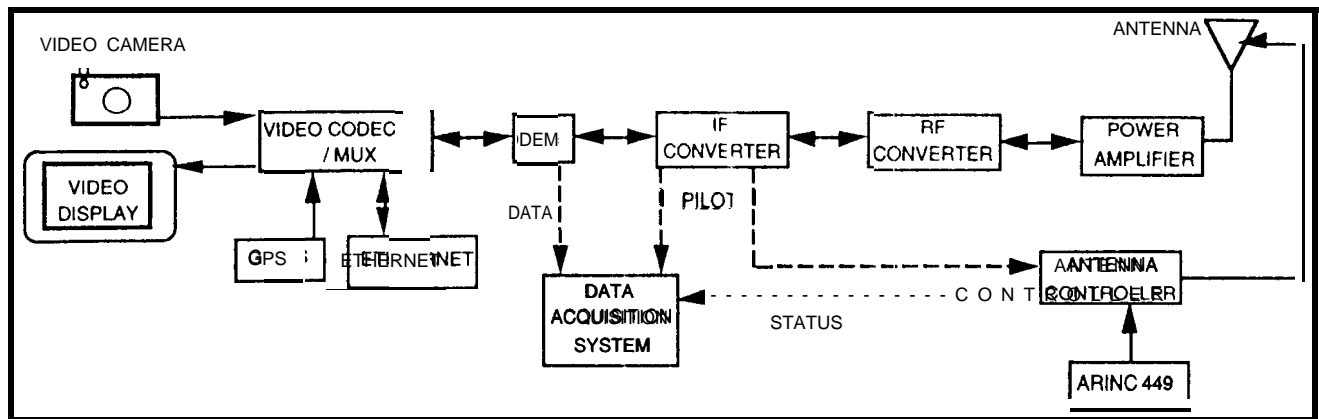


Figure 1 Block Diagram of the Broadband Aeronautical Terminal

Table 1 Link Budgets

RETURN (JPL-TO-ACTS-TO-AIRCRAFT) LINK BUDGET		FORWARD (JPL-TO-ACTS-TO-AIRCRAFT) LINK BUDGET	
UPLINK: AIRCRAFT-TO-ACTS		UPLINK: JPL-TO-AC	
TRANSMITTER PARAMETERS		TRANSMITTER PARAMETERS	
TRANSMIT POWER, DBW	20.0	TRANSMIT POWER, DBW	16.7
BPF & WG LOSSES, DB	-3.8	WAVEGUIDE LOSS, DB	-8.5
ANTENNA GAIN (W/RADOME), DBI	29.0	ANTENNA GAIN, DBI	54.7
EIRP, DBW (NOMINAL)		AVAILABLE EIRP, DBW	62.9
POINTING LOSS, DB		PERCENTAGE OF EIRP IN DATA SIGNAL, %	91.0
POL. LOSS: CIRC. W/2DB AXIAL RAT., DB	-4.1	EIRP, DBW	...
PATH PARAMETERS		POINTING LOSS	
MAX. SPACE LOSS (AT 10° ELEVATION ANGLE), DB	-2146	PATH PARAMETER	
(FREQ., GHZ)	20.0	SPACE LOSS, DB	-213.5
RANGE, KM)		(FREQ., GHZ/MHZ)	29.6
ATMOSPHERIC ATTN, DB	-0.4	ACTUAL RANGE, KM)	38000.0
RECEIVER PARAMETERS		ATMOSPHERIC ATTN, DB	-0.4
G/T: STEERABLE BEAM PEAK, DB/K	14.5	RECEIVER PARAMETERS	
POINTING LOSS (EDGE OF BEAM), DB	-0.5	POLARIZATION LOSS, DB	-0.1
BANDWIDTH, MHZ	900	G/T (EOC), DB/K	17.6
REC'D C/N0, DB HZ	48.1	POINTING LOSS, DB	-0.1
TRANSPONDER SNR IN, DB	-21.3	BANDWIDTH, MHZ	900.0
LIMITER SUPPRESSION	0.0	REC'D C/N0, DB HZ	94.1
TRANSPONDER SNR OUT, DB	-21.3	TRANSPONDER SNR IN, DB	4.5
		EFF. LIM. SUPPRESSION, DB	-0.2
		HARD LIM EFF SNR OUT, DB	4.3
DOWNLINK: ACTS-TO-JPL		DOWNLINK: ACTS-TO-AIRCRAFT	
TRANSMITTER PARAMETERS		TRANSMITTER PARAMETERS	
EIRP (EOC), DBW	41.1	STEERABLE BEAM MINIMUM PEAK EIRP	55.7
POINTING LOSS, DB	-0.2	EIRP, DBW	54.0
PATH PARAMETERS		POINTING LOSS (EDGE OF BEAM), DB	-0.5
SPACE LOSS, DB	-210.0	PATH PARAMETERS	
(FREQ., GHZ)	19.9	MAX. SPACE LOSS (10° ELEVATION), DB	-211.1
RANGE, KM)	38030	(FREQ., GHZ)	19.9
ATMOSPHERIC ATTN, DB	-0.4	MAX. RANGE (AT 10° ELEVATION ANGLE), KM	42800.0
RECEIVER PARAMETERS		ATMOSPHERIC ATTN, DB	-0.5
POLARIZATION LOSS		RECEIVER PARAMETERS	
G/T, DB/K		POL. LOSS: CIRCULAR W/2DB AXIAL RAT., DB	-4.1
POINTING LOSS, DB		G/T (W/RADOME), DB/K	...
DOWNLINK C/N0, DB HZ		POINTING LOSS, DB	-0.5
OVERALL C/N0, DB HZ	68.2	DOWNLINK C/N0, DB HZ	65.9
REQ'D EB/N0 (AWGN-SIMULATION), DB	3.0	OVERALL C/N0, DB HZ	65.9
MODEM IMPLEMENT LOSS, DB	1.0	REQ'D EB/N0 (AWGN-SIMULATION), DB	3.0
LOSS DUE TO FREQ. OFFSETS/DOP, DB	1.0	MODEM IMPLEMENT LOSS, DB	1.0
REQUIRED EB/N0, DB	5.0	LOSS DUE TO FREQ. OFFSETS/DOP, DB	1.0
LOSS DUE TO ACTS PHASE NOISE, DB	1.0	REQUIRED EB/N0, DB	5.0
DATA RATE, KBPS	384	LOSS DUE TO ACTS PHASE NOISE, DB	1.0
REQ'D EFFECTIVE C/N0, DB HZ	01.8	DATA RATE, KBPS	384.0
HARDWARE PERFORMANCE MARGIN, DB	6.3	REQ'D EFFECTIVE C/N0, DB HZ	618
		PERFORMANCE MARGIN, DB	4.0

Table 2 Video Codec Specifications

weight	<40 lbs.
height	<7"
video rates	56 kbps to 2.048 Mbps
audio rates	16 kbps to 64 kbps
image quality	high compressed image quality at all data rates
voice quality	high compressed voice quality at all data rates
power consumption	<300 Watts
BER performance	operate without degradation at $10^{-6}$
operating temperature	typical of aircraft environment
operating humidity	typical of aircraft environment
clocking	independent transmit and receive data rates
transmit capability	must be capable of transmitting while the receive is disabled, must be capable of receiving while the transmit is disabled
ports	minimum of two ports
video format	NTSC
line interface	RS449 line interface
mounting scheme	rack mount hardware required

Figure 2 Slotted Waveguide Antenna

Figure 3 Aeronautical Radome on Rockwell Saberliner 50

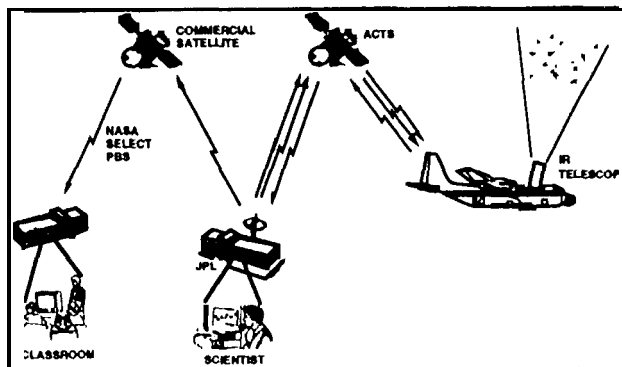


Figure 4 KAO Experiment

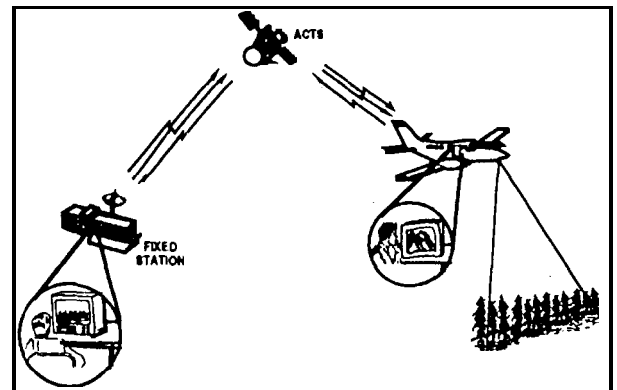


Figure 5 Rockwell/Collins Experiment